

Nano Photoelectric Material Structures – Photonic Crystals

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Abstract. Photonic crystals are periodic dielectric structural materials that have photonic band gaps, and are divided into one-dimensional, two-dimensional, and three-dimensional structures based on their spatial distributions. One-dimensional photonic crystals have already found real-world applications. Three-dimensional photonic crystals are still in the experimental phase in laboratories. Due to their superior characteristics, photonic crystal materials are sure to be widely developed and applied in the future. This paper briefly introduces the principle of photonic crystals, facts about their theoretical research, production and preparation of materials, as well as their related applications. Photonic crystal materials have a lot of potential, and could be one of the most significant materials of this century. Since the concept was proposed in the late 80's of the previous century, the research and application of photonic crystals has advanced significantly. Currently, photonic crystals are already used in fiber optics as well as semiconductor lasers. This paper introduces the structures of various types of photonic crystals, including photonic crystals with semiconductor and fiber optic material bases, and describes some of the special optoelectronic characteristics and possible applications of photonic crystals. Photonic crystals can be used in the production of many new types of optoelectronic devices. Most significantly, they can dramatically reduce the size of components and result in dense integration. Photonic crystals are expected to have a revolutionary impact on the development of optoelectronic technologies.

Introduction

Over the past 50 years, semiconductor technologies have rapidly developed, bringing a great deal of convenience into people's lives. With the reduction in size of integrated circuits and dense integration of circuits, the physical limits of microelectronic technologies are now viewed as a major restricting bottleneck factor in the development of integrated circuits. When component sizes become smaller, the interference between components becomes more severe. Electronic signals also develop signal delays due to dense integration of circuits. In addition, there is also the problem of heat dissipation caused by the electrons in components. Currently, scientists are trying to use photons to replace electrons as information carriers in hopes of solving these types of issues.

In 1987, E.Yablonovitch proposed the concept of photonic crystals while conducting research on inhibiting spontaneous radiation^[1]. At almost the same time, S.John also independently proposed the same concept while discussing photon localization^[2]. The proposal of photonic crystals has shown people a new mechanism for controlling photons, bringing new life and vigor into fields such as communication technologies and photoelectric technologies.

In the field of photonics, we often wish to use matter to change the behavior of light, using mechanisms such as polarization, electroluminescence, and optical wave guiding to take advantage of light in applications including liquid crystal displays, light-emitting diodes, and fiber optic communications. Most of these characteristics are achieved by changing the chemical structures of matter within the molecular scale of the materials. However, the electromagnetic characteristics of light waves inside various materials can also be modified by manipulating certain aspects of physical structures in the wavelength range of 100nm~1mm.

As opposed to the characteristics of electrons in semiconductor crystals, photonic crystals are a type of artificial "crystal" structure formed by aligning dielectric materials with different dielectric constants according to a given reoccurring sequence in the same space. The dielectric constants of

photonic crystals are a periodic function of space. Similar to the electrons in semiconductor materials forming energy band structures under the influence of periodic electric fields, photon energy in photonic crystals also have band structures and there are photonic frequency band gaps in the areas between bands. Photons whose frequencies fall within the frequency band gaps cannot propagate in the crystals, forming a type of photonic insulator. In the current electronics industry, because of the relationship between speed and capacity, light-wave components are becoming more and more in demand. These types of photonic crystals could have very wide applications in the production of light-wave components, and are viewed as a very new and important next-generation optoelectronic material.

Principle and Applications of Photonic Crystals

The fundamental principle of photonic crystals is Bragg diffraction, which is light waves producing destructive interference in photon crystals, resulting in photon energy band structures similar to electron energy bands, and further producing photon band gaps (PBG). Similar to impurity energy gaps in semiconductors, by introducing impurities in photonic crystals, localized photon impurity films can be produced within band gaps. Recently, it has been proven in laboratories that photonic crystals with impurity films can indeed be produced^[3]. The photon localization of impurities in two-dimensional photonic crystals can be calculated using the Wannier function method, which is also the impurity state^[4]. The band gaps in photonic crystals or the impurity states in band gaps can easily allow or restrict the passage of a photon of a certain frequency. This characteristic gives photonic crystals the potential for wide application. Using photonic crystals, many high-quality optical instruments and optoelectronic devices, such as single-mode transmission optical fibers, high-quality filters, micro-harmonic vibration cavities with high Q values, and lasers can be produced. The types of defects in photonic crystals are shown in figure 1. Figure (a) shows a photonic crystal with a point defect. Since the area around the point defect consists entirely of optical insulators formed by photonic crystals, the distribution of light waves in space will be limited to the area near the point defect, which means that the photon will oscillate back and forth at the point defect. Therefore, this is equivalent to a micro cavity. Figure (b) shows a photonic crystal with a line defect. Similarly, light cannot propagate to nearby photonic crystals, and can only propagate along the defect. Therefore, it is equivalent to a waveguide. By changing the size of the defects or the dielectric constants, the states of the impurities can also be changed. With proper design, impurities with specific energies or specific spatial characteristics can be produced according to application requirements. This is why photonic crystals have become one of the most widely researched topics in the optoelectronic and materials fields in recent years.

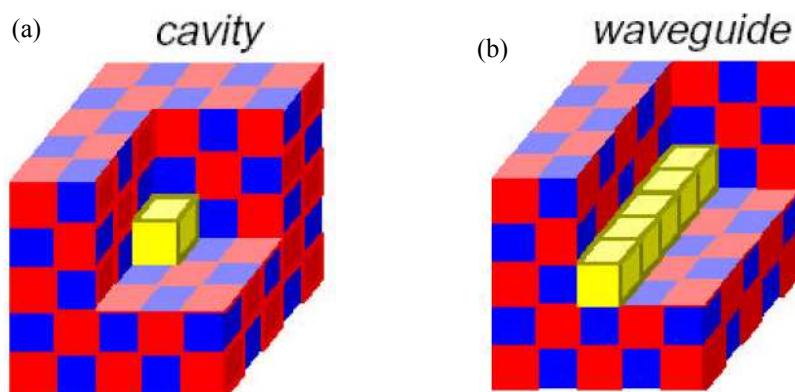


Figure 1: Types of photonic crystal defects (a) this figure shows a defect (b) this figure shows a line defect.

Producing Photonic Crystals

It is widely recognized that photonic crystals have enormous application potential, which is why photonic crystal production technologies are currently being researched and developed by many researchers across the globe. In terms of the number of dimensions of photonic crystals, the production of photonic crystals can be divided into one-dimensional, two-dimensional, and three-dimensional photonic crystal production. Since the production of one-dimensional photonic crystals can be achieved through various plating techniques, we will mainly focus on the production of two-dimensional and three-dimensional photonic crystals.

Two-Dimensional Photonic Crystal Process Development History

In the research of two-dimensional photonic crystals, the production of microwave photonic crystals can be accomplished by using dielectric poles (with diameters of several mm). This type of process is relatively simpler. However, when the light wavelengths shrink to the micron or sub-micron level (corresponding to visible light and infrared light), the processes become very difficult. Even so, research personnel take full advantage of various nano-process technologies as well as mature semiconductor processing techniques to produce visible light and infrared light photonic crystals. For example, in 1993, Wendt et al. used electron beam direct writing and reactive ion beam etching to produce two-dimensional AlGaAs thin films (panel) photonic crystals on GaAs substrates^[7]. First, they took advantage of the single-spot exposure of electron beam direct writing to define the two-dimensional photonic crystal structural patterns on electronic glue, then, reactive ion beam etching technology is used to move the final pattern onto AlGaAs thin film. The advantage of this type of technology is that it can significantly reduce the time required for the electron beam direct writing system to define the pattern. Compared to multiple-point development technologies (the technology currently most used), it only required one tenth of the time required, or even less^[8]. However, single-point development technologies have the disadvantage of not being able to perform development level correction (proximity effect). If this issue can be overcome, the future for single-point development will become much brighter. Krauss et al. used multiple-point development technology and reactive ion beam etching technology to produce GaAs substrate photonic crystals (as shown in Figure 2)^[9].

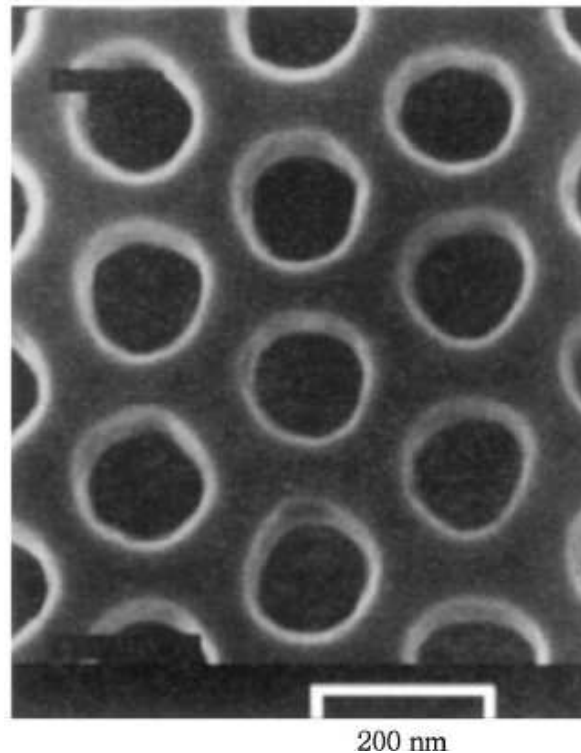


Figure 2: Two-Dimensional GaAs Photonic Crystals Produced using Multiple-Point Development Technology

In addition to using electron beams and reactive ion beam etching to produce two-dimensional photonic crystals, some scientist also use chemical methods to etch micro pores, thereby obtaining two-dimensional photonic crystals. For example, large aspect ratio periodic micro pores can be obtained using aluminum oxide anodes and chemical erosion methods^[10,11]; large aspect ratio micro pores can also be obtained under lighted conditions using n-type silicon $\langle 110 \rangle$ surface etching with hydrogen fluoride solution. The produced photon crystal micro structures are shown in Figure 3^[12]. Besides the aluminum oxide anode method, liquid corrosion methods usually can only produce two-dimensional photonic crystals with larger apertures. This class of photonic crystals has a basic photon band gap wavelength in the range of 10 —30 μm .

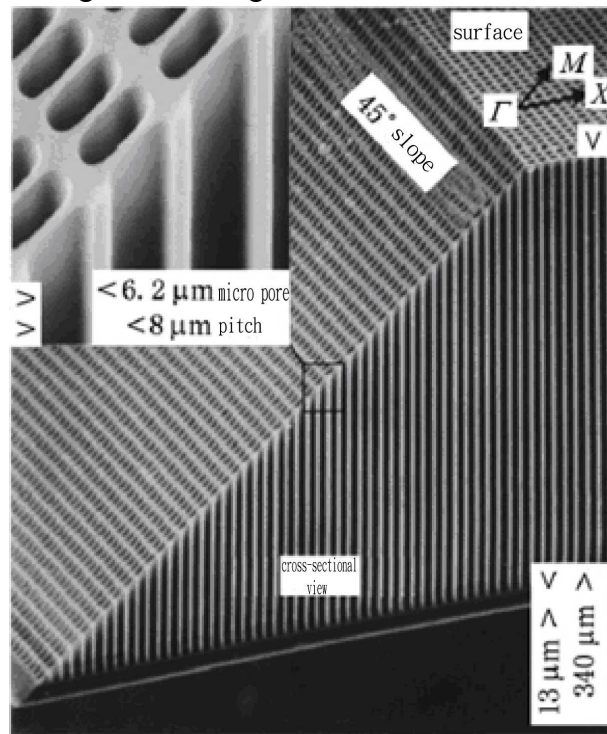


Figure 3: Two-Dimensional Photonic Crystal Produced using a Porous Silicon Process

The homogeneity of the micro structure of photonic crystals directly affects the physical characteristics of photonic crystals. One of the important issues that current processes need to overcome is being able to produce photonic crystals with apertures that are exactly the same. Small differences in the micro pores could cause changes in the resonant frequency, resulting in the device losing its function, especially with devices that are reused densely, whose frequency gaps are 100 GHz (corresponding to a wavelength gap of 0.67 nm). In a two-dimensional planar GaAs photonic crystal, to mane the wavelength difference below 0.67nm in a cavity formed by losing a pore, the difference in aperture diameters for the surrounding micro pores should be close to or smaller than $\Delta d = \lambda^2/4n \approx 0.05 \text{ nm}$ ^[12], which is a very strict requirement for processes. Finding ways in which to overcome process limitations as well as creating the precision required by applications will be the key to whether or not phonetic crystals can further advance and be further applied.

Two-Dimensional Photonic Crystal Process Development

Three-dimensional photonic crystals that have complete energy gaps can perform propagation manipulation of light in all directions in space, making it a focus and a problem in the research of photonic crystals. The key to realizing three-dimensional photonic crystal performance, spontaneous radiation must be suppressed and high-Q micro cavities must be produced. Therefore, many research teams across the globe are being dedicated to the research of three-dimensional photonic crystal production and other relative technologies. Compared to two-dimensional photonic crystal processes, three-dimensional photonic crystal processes are much more difficult. Since the concept of photonic crystals was proposed, many research personnel have researched how to produce three-dimensional photonic crystals through self-assembly. After 20 years of hard work,

three-dimensional photonic crystal production technologies have advanced significantly. Overall, currently known three-dimensional photonic crystal production methods include: the colloidal microsphere self-assembly method, the multi-beam interference method, the phase grating method, the multi-photon polymerization method, the glancing angle deposition method, the auto-cloning technology method, the electron beam direct write method, and the reactive ion beam etching method.

The microsphere self-assembly method was the first method to be used in the production of three-dimensional photonic crystals. Face-centered three-dimensional periodically arranged colloidal photonic crystal structures can be self-assembled by using mono-dispersed polystyrene or silica microspheres^[13,14]. However, this type of colloidal photonic crystal in fluids is very unstable and very hard to control, and it is very difficult to apply in real applications. Therefore, the growth method was further advanced to using microspheres to naturally deposit under the influence of gravity. After the solution evaporates, solid three-dimensional photonic crystals are obtained, which are called opal^[15-18]. Photonic crystals with opal structures are shown in Figure 4.

The methods of electron beam direct writing, reactive ion beam etching, vapor deposition, surface polishing, and wet etching can be combined to produce three-dimensional crystals. This method can be used to produce three-dimensional photonic crystals with specific defects. This method has long been used to produce infrared photonic crystals with photon band gaps. The Lin team was the first to produce photonic crystals with woodpile structures^[19]. However, because this method requires expensive equipment and many iterations of electron beam direct writing since each layer requires the iteration of one loop, the process is very time-consuming. In addition, an error in any step in the process will result in un-repairable damage to the entire product. Only a small number of laboratories in the world are engaging in this type of research^[20]. Due to current process technology restrictions, it is also difficult for this type of technology to produce photonic crystals with band gaps close to visible light. However, Qi et al. have proposed ways to further improve the process, thereby enhancing the process speed and efficiency^[21]. The photonic crystal production flow as well as the produced photonic crystals is shown in Figure 5.

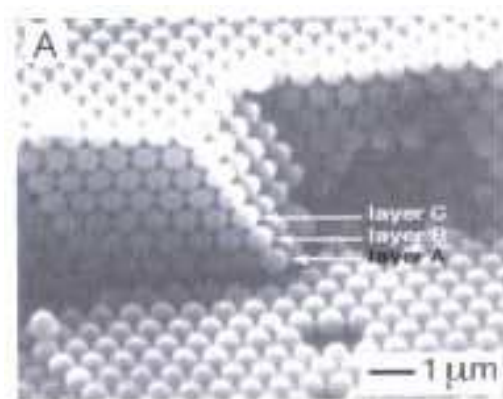


Figure 4: An Example of a pearl structure (opal)

Figure 5 (A) Production Flow Diagram for a Three-Dimensional Photonic Crystal Produced using a type of Electron Beam Etching; (B) (a) a scanning electron microscope view of the photonic crystals produced, (b) and (c) highly-magnified scanning electron microscope view of photonic crystals

In order to produce three-dimensional photonic crystals, scientists have developed many new process technologies. Multiple-beam interference is also a relatively good production method^[22,23]. All crystal types can be formed using multiple-beam interference, including face-centered cubes, diamond structures, and body-centered cubic structures.

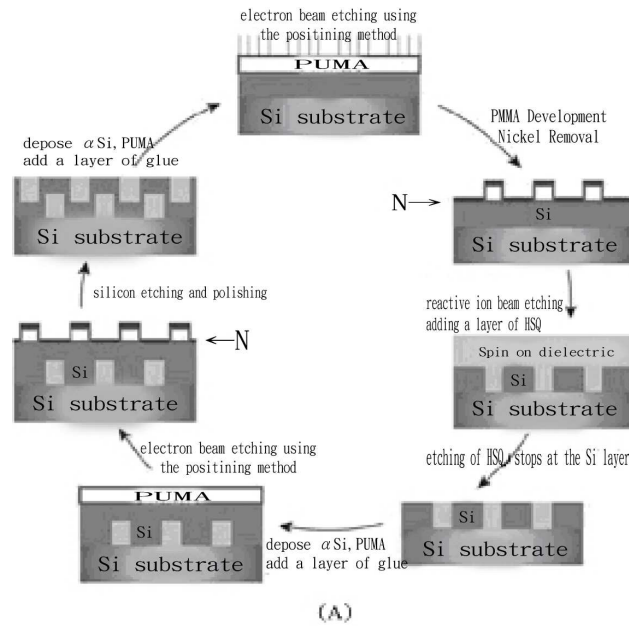


Figure 5 (A) Production Flow Diagram for a Three-Dimensional Photonic Crystal Produced using a type of Electron Beam Etching

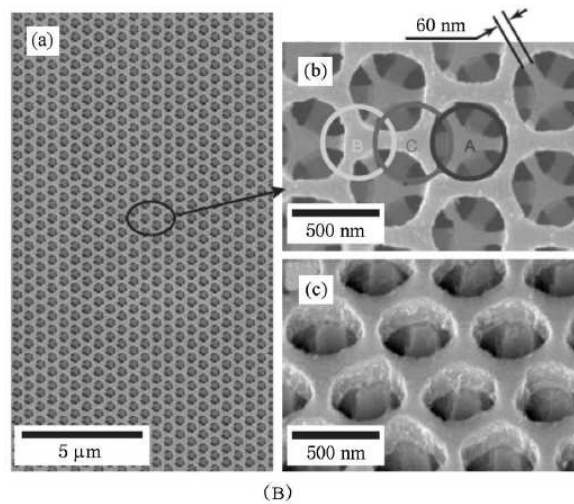


Figure 5 (B) (a) a scanning electron microscope view of the photonic crystals produced, (b) and (c) highly-magnified scanning electron microscope view of photonic crystals

Crystals can be obtained by adjusting the phases and polarizations of the various light beams. However, they are restricted by the wavelengths of the lasers that are used. There is currently no way to produce three-dimensional photonic crystals with complete photon band gaps in the visible light region.

From the technical perspective of the processes, three-dimensional photonic crystal production methods can be categorized into “top-to-bottom,” “bottom-to-top,” or a combination of both the “top-to-bottom” and “bottom-to-top” methods. Overall, to this day there have not yet been any reports of any photonic crystals having complete photonic band gaps within the visible light spectrum. This happens to be a very important application area for photonic crystals, therefore, if photonic crystals with complete photonic band gaps in the visible light spectrum can be produced, it would no doubt be a significant breakthrough.

Conclusion

With photonic crystals, we can find many new optoelectronic phenomena and develop new types of components and application. Regardless of whether our goal is to advance basic research or to find real applications, we will need to find new process technologies to produce new photonic crystal structures and high-quality components.

In reality, the future direction of the entire field of photonic crystal research is very clear, and includes ultra-low critical operations, ultra-high Q values, perfect single-mode operations, optimization of component stability, as well as high-power output, etc. The first three items are especially critical for realizing “photonic integrated circuits.” It can be anticipated that even more admirable designs and achievements in this area will be shown to the world in the near future.

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